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Trio-PV Monitor: A Smart IoT-Based Instrument for Continuous and Reliable Monitoring of Solar PV Installations †

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Abstract: This paper introduces a Trio-PV monitor: a smart IoT-based instrument for the continuous and accurate monitoring of solar PV systems. The instrument is a synergistic combination of electronic hardware, desktop applications and a website. It has been conceived to provide monitoring, storage, and sharing as well as to perform statistical operations on solar energy-related data collected at any chosen site. The instrument features high flexibility, with the capacity of monitoring PV plants of up to a 90 kW rating. It is intentionally equipped with large-range weather-proof sensors, permitting monitoring and evaluation across different seasons and geographical areas. The proposed instrument targets six keys operating variables of a PV systems, namely irradiance, panel-temperature, ambient temperature, humidity, PV current and voltage. The automated design of the Trio-PV monitor allows for continuous operation for 12 h within a day. The instrument has been used to monitor simple 30 W solar PV-DC connected systems, with acquired results revealing it practical suitability and soundness. The friendly user interface of the system allows a graphical visualization of monitored parameters in real time through an installed desktop application. Finally, the IoT competence of the proposed instrument extensively allows data acquisition and the monitoring of a PV system from any location in the world. It is envisioned that the developed instrument would be a leverage package for data acquisition and the monitoring of PV system installations in developing countries and especially in Cameroon where access to information on PV systems is still highly costly and unreliable.

Keywords: Trio-PV system monitor; PV system monitoring; PV parameters; PV data; IoT-based PV system monitoring

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1. Introduction

Cameroon's electricity supply, which is highly dependent on hydropower, experiences roughly ten outages each month that last around two hours on average. As a consequence, the frequency of power interruptions and load shedding has become significant, especially during seasons of low rain density [1]. Faced with such a situation, the integration and accommodation of other energy sources into the grid emerges as a reliable and promising energy solution. Currently, several attempts are being made to explore renewable energy sources as potential alternatives [2,3]. During the last few years, several studies have consistently established that the entire territorial distribution of Cameroon is endowed with a great potential of solar energy, noticeably with about 900 trillion kWh of solar energy reaching its land per annum [4]. Most recently, studies have shown that the country has an estimated irradiation exceeding the order of 5 kWh/m^2 day, representing a favorable potential of solar energy [3,5,6]. As a response, a sincere and effective practical materialization of solar energy would inevitably benefit the country in terms of development and economic advancement.

Operationally, the performance of a PV system is contingent on the location and the condition of PV panels. Particularly, weather conditions have an inherent influence on the operation of these systems [7]. As a consequence, close monitoring and performance evaluation with respect to environmental changes can help in the enhancement of their performance. Furthermore, continuous monitoring is a vital requirement for making informed short-term or long-term corrective measures.

Monitoring the generation of electric energy is essential to statistically analyze the yields of PV installations and to validate the technical and economic feasibility of the system [8]. The monitoring of PV systems is generally intended to measure the operational energy efficiency, which is an important characteristic of any energy conversion device, in order to determine how much energy captured by the panels is converted and effectively transfer into a load. After studying related works on PV system monitoring [9–11], it is realized that the most prominent operational and meteorological parameters are solar irradiance, panel temperature, ambient temperature, humidity, PV voltage and current, while some other parameters may be configuration-dependent. A monitoring system consists of numerous sensors, which provide information on different variables under various conditions. This information can be used by the operators in making decisions related to utilization, replacement, and system reliability [12].

A number of data-logging devices have been developed for the monitoring of PV systems in recent years. The development of PV monitoring systems and data acquisition systems has been the subject of several investigations. It has been demonstrated that using PV modules for outside applications according to the manufacturer's manual could produce botched outcomes and may induce system dissatisfaction [10]. In order to maximize PV system efficiency, reliability, and operational enhancement, PV variables must be observed in outdoor conditions. A significant length of time is required to obtain output parameters of the system as well as the metrological data.

It is noteworthy that a typical commercial monitoring system can be very expensive, especially for low-income countries. A cost-effective, reliable, and efficient system for PV monitoring and data acquisition is thus necessary. A series of works related to the monitoring of PV systems have been limited to wired data acquisition systems, using LABVIEW license software. Although effective, such acquisition systems come along with a high costs and moderate accessibility. To surmount such limitations, other variables have been investigated in wireless systems, with acquisition software constrained by license and clouds services. In addition, the cost of software licenses severely restricts the accessibility of such a system for low-income counties [13].

In the context of Cameroon, there is very limited information pertaining to the suitability of PV system installation location, which is a consequence of there being little or no reliable operational data. Weather stations have been installed in a few major towns but they only provide information on the meteorology and do not correlate this to the power production of a PV plant. It is noteworthy that each monitoring and data acquisition system is designed for a specific context. It may contain deficiencies in its design when employed for a different context or environment. For example, a 5 kW system was proposed to aid managers in obtaining PV variables via the use of a wireless link [14]. The latter work uses LDR and LM5 to seek measurements of solar irradiance and temperature. It is well known that the LDR as a sensor of solar irradiance has a very low spectral range, and as a consequence, compromises the accuracy and reliability of data collected. Furthermore, the latter study does not take into consideration weather variability in the choice of sensors. The choice and conditioning of sensors are crucial considerations for the yearly and continuous monitoring of PV systems. Cameroon in particular has four climatic zones and two principal seasons. Most temperature and humidity sensors are prone to failure in the rainy season, constraining the deployment of monitoring systems to the dry season.

The PV data acquisition and monitoring instrument developed in this work is a synthesis of many past ideas while it also improves the ease of integration into any PV plant and considers harsh environmental changes and rampant power outages. It takes into consideration the difficulty of the constant physical collection of data. Thus, the entire system is fully automated with minimal or no human interference. Monitored data are stored locally and in the cloud. The desktop application permits local storage, and syncing enables the data to be stored in the cloud for exploitation at anytime and anywhere in the globe.

2. Design of the Trio-PV Monitoring System

The proposed data acquisition and monitoring instrument is structured with three key components, namely an electronic hardware system, a desktop application and a website (Figure 1). These components are designed, built and synergistically merged to form the trio system that monitors, stores, shares and provides an analysis of the solar energy-related data at any chosen site. These components are discussed in subsequent sections of this paper.

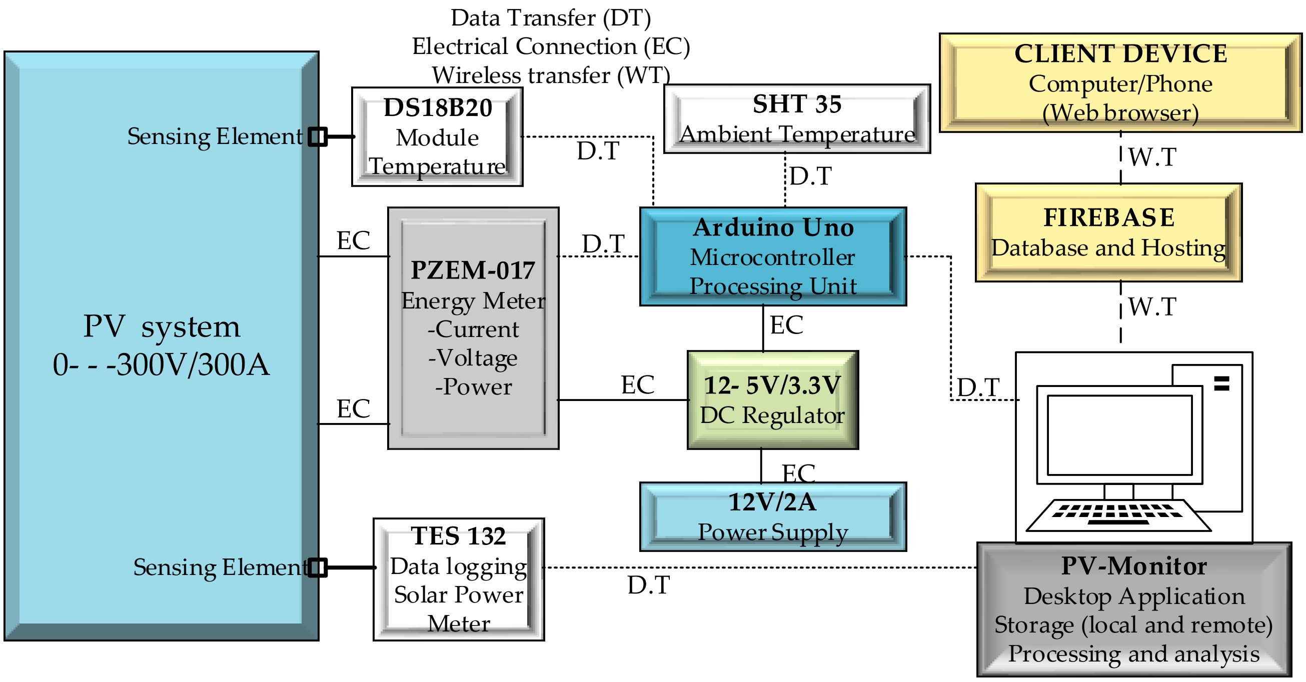


Figure 1. Conception block diagram of the Trio-PV monitoring system.

2.1. The Electronic Hardware System

The electronic hardware system comprised sensors (of temperature, humidity, voltage and current), a power supply, a voltage regulator, a controller (Arduino Mega), pyranometer and other accessories, as seen in Figure 1. The sensors and controller are driven by the firmware developed in C++ using the Arduino IDE. The electronics hardware were well packaged with labels/sockets for the inputs and outputs of various signals (Figure 2). It was made as portable device that can be interfaced with ease on any PV system for the monitoring of the most prominent operational and meteorological parameters.

Figure 2. The packed electronic hardware system.

2.1.1. Current, Voltage and Power Measurement

The PZEM-017 module is a DC communication module. It is used to measure and record voltage, current and power from the PV system. This DC communication module can measure DC voltages of up to 300 V with a resolution of ± 0.01 V. For current measurement, the resolution is ±0.01 A, but an external shunt needs to be installed. The 300 A operation was chosen for the proposed monitoring instrument, enabling measurements of up to 90 kW. The broad operating range and low cost of this module align with the low cost requisite of the developed system. In order to confirm the accuracy of this module, it was compared against a standard millimeter, which revealed a negligible discrepancy. Additionally, the PZEM-017 has an in-built RS485 communication interface that makes use of a Modbus-RTU protocol similar to that of most industrial devices. By using the UART to RS485 converter and its accompanying software, measured values can be displayed on a personal computer (PC).

2.1.2. Temperature and Humidity Measurements

The Trio-PV monitor instrument uses a DS18B20 digital thermometer, designed to operate through a serial communication protocol with an Arduino microcontroller unit, for temperature sensing on a PV module. It has an accuracy of ±0.5 °C, and operates in the range of −55 °C to +125 °C. Kapton tape was used to fit the waterproof version of the DS18B20 sensor on the backside of the PV module. To measure the ambient temperature and humidity, the Taidacent Corrosion and Acid Resistance I2C digital sensor (SHT35) was used. It has an accuracy of ±0.2 °C in the range −20 °C to +100 °C. It measures relative humidity from 0% to 100%.

2.1.3. Solar Irradiance Measurement

The Trio-PV monitor instrument uses TES 132 Solar Power Meter for the measurement of solar irradiance. It is a precision instrument used to measure solar irradiance in the field with data logging capacity. It is fully cosine-corrected for the angular incidence of solar radiation. The instrument has a spectral response from 400 nm to 1000 nm. The range of measurement of solar irradiance is 200 W/m^2 to 2000 W/m^2 with a resolution of 0.1 W/m^2, an accuracy of ±10 W/m^2 and a sampling rate of 1 times/second. The designed PC-based application was easily managed and coordinated using the PC.

The software component of the instrument consisted of a Desktop app, a controller firmware and a website. The desktop app was developed in HTML, CSS, JavaScript and Python using the electron framework through visual studio code. The desktop app displays or previews the sensor readings in real time and can also replay the past PV data records. It saves the readings locally and equally uploads them to a firebase database. The app performs statistical operations on the readings such as minimum, maximum, mean, median and mode. It plots the line curves, and vertical and horizontal bar graphs of the sensor readings with time. The app can also share the readings in a spreadsheet format for processing as defined by the user. Figure 3 is a screenshot of the app's interface.

Figure 3. Screenshot of the desktop data acquisition app.

2.2. Desktop Application

The website, on the other hand, was developed using nodeJs and firebase hosting. It receives and previews sensor readings uploaded by the desktop app, and filters and offers readings for download in a spreadsheet format as well. Figure 4 is a screenshot of the website, which can be accessed using a smartphone or computer.

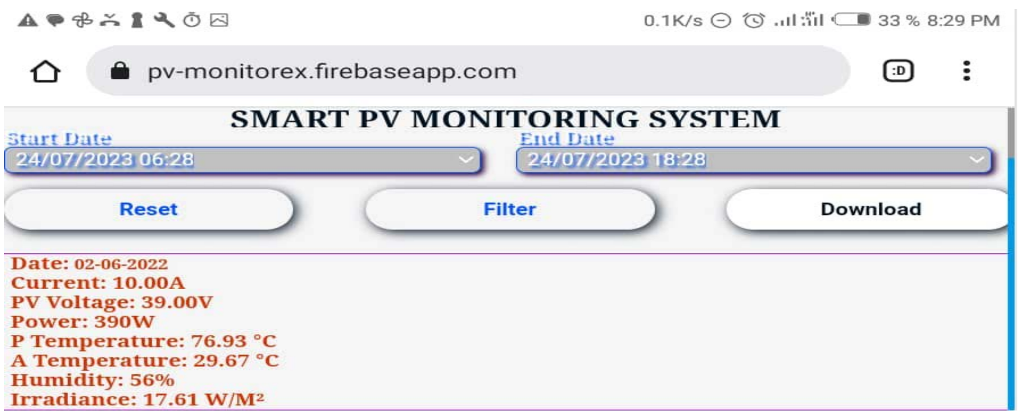


Figure 4. Screenshot of the website.

2.3. Utility Software Required for the Trio-PV Monitor Device

Visual studio code is used to code the desktop application and the website application. Python Version 3.9.12 is packaged alongside the application and runs the scripts responsible for the statistical operations on the sensor readings. NodeJs is the website's backend technology and is equally a major component of the electron framework. Arduino IDE is used to code the sensor controller's firmware. Adobe XD is used to design the app's icons, its background graphics and the UI components tests. A packaging engine carries out the final packaging of the application into a .spar file from which the extraction engine will create a distributable installer for the desktop app.

2.4. Plugins and Libraries Required

The desktop app uses the Fs-extra library to perform backups, restore operations of the local database and to equally export plotted graph images. For communication between nodeJs and python, the Python shell library is used. Communication between the hardware and the software is carried out over the serial port enabled by the electron serial port library. Backend operations of syncing the local database with the cloud firestore are achieved with the use of the firebase admin library. Electron forge is used for the pre-packaging of the app components with the electron. The electron rebuild library builds the serial port library for the windows OS. SheetJs library is responsible for creating the spreadsheet files from formatted sensor reading data both locally and in the web application. The nedb library is the local database engine used by the desktop app. In Python, the Numpy library is used to format the readings into arrays on which matplotlib and scipy libraries work. The matplotlib library is used to plot time value graphs for the sensor readings over desired time ranges while the scipy library is used for the statistical analysis of sensor readings.

3. Testing of the Trio-PV Monitoring System

3.1. Geographical Site

The testing of the Trio-PV monitor device was carried out on the campus of the University of Dschang situated in the West Region of Cameroon. The testing site has the following geographical coordinates: latitude: 5°27′0′′ N; longitude: 10°04′0′′ E; and elevation: approximately 1380 m above sea level. This site was chosen to ease the monitoring of the testing process and also to make first-hand information available to researchers and scientists in the university community.

3.2. PV Plant Characteristics

For a test demonstration, a 30 Wp PV system was considered. The PV system constituted a 30 Wp solar Renogy panel (RNG-30-SS) and a load made up four DC lamps of 12 V and 9 W, each connected in parallel. The intention of the described connection is to have a load that can consume up to 36 W. The load system was slightly oversized to permit the measurement of power greater that in the standard test condition (STC) values. The built trio-PV monitoring systems in operation are shown in Figure 5. A Renogy module was chosen since it is a reference module with standard specifications. The overall objective is to integrate the system on a 1 kW rooftop plant on the campus, in order to collect meteorological data and monitor the performance of the plant at least for one year. However, the system can be used on any plant of up to 90 kW as previously described. The data collected, particularly on temperature and irradiance, will be pivotal to researchers and engineers, especially those in Cameroon working on solar energy. Testing was carried out for three continuous days (3 September to 5 September 2023).

Figure 5. Trio-PV monitoring system in operation.

4. Results and Discussion

Figure 5 shows the functional system collecting the environmental and PV system's operational parameters. The data terminal of the application was seen to be active and all the data channels were functioning. The user can selectively pause some channels while the active channels record the data. Table 1 is a quantitative description of the simple PV system data that was monitored for 12 h on 3 September 2023 in Dschang.

Table 1. Quantitative description of the monitored PV system.

Trio-PV-Monitor Monitored PV System Variables	Maximum Measurements		Minimum Measurements		Average Day's Measurement
	Value	Time	Value	Time	
Relative Humidity (%)	98.56	06:01:00 AM	46.92	12:11:42 PM	77.3989
Irradiance (W/m^2)	1383.3	13:45:58 PM	0.26	06:00:35 AM	275.4443
Temperature (Ambient)	36.26	11:36:10 AM	17.54	06:00:35 AM	24.0215
Temperature (PV)	42.50	10:24:04 AM	17.19	06:00:35 AM	25.8290
Voltage (V)	11.80	13:45:58 PM	0.00	06:00:35	9.2167
Current (A)	2.67	13:45:58 PM	0.00	06:00:35	0.5081
Power (W)	31.50	13:45:58 PM	0.00	06:00:35	5.1276

Data were collected from 6:00 AM to 6:00 PM on 3 September 2023. It was a bright day with about an hour of rainfall from 12:30 PM to 1:30 PM. From 4 AM, the day was characterized by small drizzles of rain though the atmosphere was without cloud coverage. To plot graphs using the app, the data analysis tab was selected and the data within a chosen time frame could be plotted with a user-defined interval. Such flexibility is permitted as shown in the screenshot in Figure 6a. Figure 6b shows the variation in solar irradiance on 3 September 2023 from 6 AM to 6 PM. The data can also be exported in excel format and plotted in excel or MATLAB. Figure 7 shows a graph of the operating power (Watt), the solar irradiance (Wm^{-2}) and operating current (A), the ambient temperature (°C), the relative humidity (%) and the module temperature (°C).

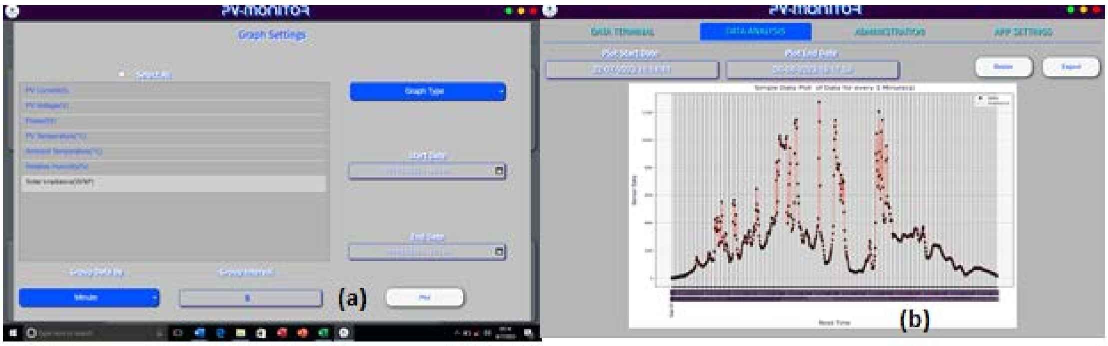


Figure 6. (**a**) App graph setting interface. (**b**) Solar irradiance variation.

As seen from Table 1 and the graphs in Figure 7, a maximum power of 31.5 W was drawn with the 36 W load at about 1:45 pm. At this time, the solar irradiance was at the maximum for the day and the operational current was 2.67 A. The values of the power and current are greater than the operational values at STC. This is an expected outcome given that the solar irradiance at this time was 1338.3 W/m^2 and the module temperature was 26 °C. Also given the voltage restriction on the load (the load was rated at 12 V), the load had to draw more current to make up for the power generated at this irradiance value. The minimum operational values were obtained at 6:00 am when the solar irradiance was the least for the day. From Figure 7, a direct correlation between solar irradiance, current and power can be observed. These results show that the trio-PV monitoring system is suitable and effective to investigate, collect and carry out statistical operations on the operational information of a PV system to evaluate its performance under outdoor conditions.

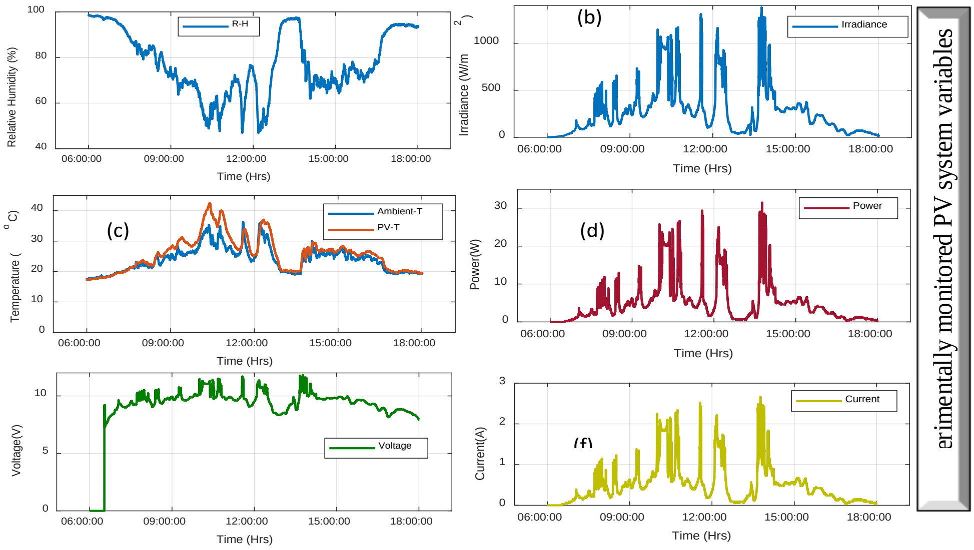
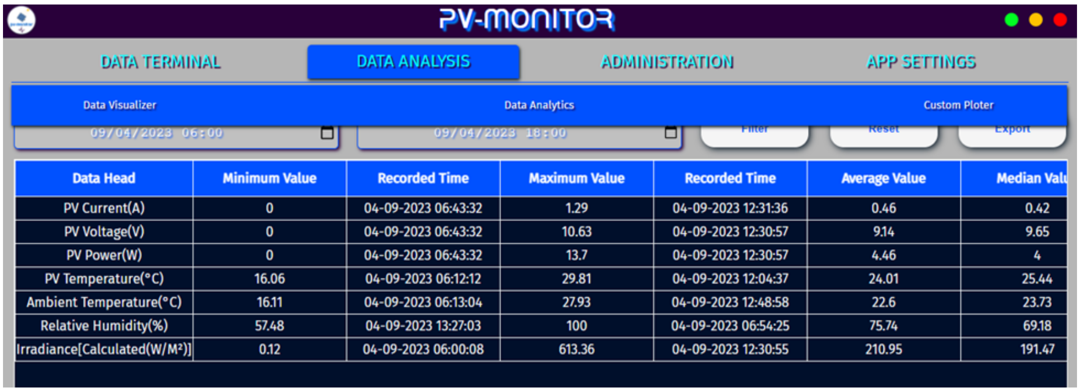


Figure 7. Experimental measurement of the PV system recorded by the Trio-PV monitor device on a 30 W PV system, 3 September 2023. (**a**) Relative humidity, (**b**) irradiance, (**c**) ambient temperature and PV temperature, (**d**) system power, (**e**) system voltage, and (**f**) system current.

For data analysis, the data analytics tab can be used to visualize the statistical operations on data for a particular filtered interval. On 4 September, from 6 am to 6 pm, the app provides useful statistical information, as seen in Figure 8.



Data Head	Minimum Value	Recorded Time	Maximum Value	Recorded Time	Average Value	Median Valu
PV Current(A)	0	04-09-2023 06:43:32	1.29	04-09-2023 12:31:36	0.46	0.42
PV Voltage(V)	0	04-09-2023 06:43:32	10.63	04-09-2023 12:30:57	9.14	9.65
PV Power(W)	0	04-09-2023 06:43:32	13.7	04-09-2023 12:30:57	4.46	4
PV Temperature(°C)	16.06	04-09-2023 06:12:12	29.81	04-09-2023 12:04:37	24.01	25.44
Ambient Temperature(°C)	16.11	04-09-2023 06:13:04	27.93	04-09-2023 12:48:58	22.6	23.73
Relative Humidity(%)	57.48	04-09-2023 13:27:03	100	04-09-2023 06:54:25	75.74	69.18
Irradiance[Calculated(W/M²)]	0.12	04-09-2023 06:00:08	613.36	04-09-2023 12:30:55	210.95	191.47

Figure 8. Screenshot from app indicating statistical operations.

5. Conclusions

A Trio-PV monitor device is developed and tested. The instrument was tested in the Dschang University campus for a period from the 3rd to 5th September 2023 on a 30 Wp PV system with a 36 W load. The system captured data on the operating power (Watt), solar irradiance (Wm^{-2}), operating current (A), ambient temperature (°C), relative humidity (%) and module temperature (°C). The data could be displayed graphically. This results show that the trio-PV monitoring system was suitable and effective to acquire data and monitor a PV system to evaluate its performance under outdoor conditions

6. Future Work

It is expected that the most prominent operational parameters and weather parameters will continue to be collected for at least one year. We also intend to develop and incorporate a cheap and efficient method of measuring solar irradiance. As a result, the price of the Trio-PV monitoring device will be reduced significantly.

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